Higher-order-mode absorbers for energy recovery linac cryomodules at Brookhaven National Laboratory

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Several future accelerator projects at Brookhaven for the Relativistic Heavy Ion Collider (RHIC) are based on energy recovery linacs (ERLs) with high-charge high-current electron beams. Their stable operation mandates effective higher-order-mode (HOM) damping. The development of HOM dampers for these projects is pursued actively at this laboratory. Strong HOM damping was experimentally demonstrated both at room and at superconducting (SC) temperatures in a prototype research and development (R&D) five-cell niobium superconducting rf (SRF) cavity with ferrite dampers. Two room-temperature mock-up five-cell copper cavities were used to study various damper configurations with emphasis on capacitive antenna dampers. An innovative type of ferrite damper over a ceramic break for an R&D SRF electron gun also was developed. For future SRF linacs longer cryomodules comprised of multiple superconducting cavities with reasonably short intercavity transitions are planned. In such a configuration, the dampers, located closer to the cavities, will be at cryogenic temperatures; this will impose additional constraints and complications. This paper presents the results of simulations and measurements of several damper configurations.

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I. INTRODUCTION

The Collider-Accelerator Department at BNL is actively working on various accelerator projects based on high-current superconducting rf (SRF) energy recovery linacs (ERLs): (1) a research and development (R&D) energy recovery linac facility [1]; (2) the envisioned electron-ion collider [2]; and (3) coherent electron cooling [3]. The requirements for high current, high brightness, and high charge in these projects all require development of effective higher-order-mode dampers.

The R&D ERL facility is expected to operate with a high current up to 0.3 A, or with high-charge bunches up to 5 nC. It is based on a five-cell SC linac [4] and a half-cell superconducting (SC) photoinjector rf electron gun [5], both operating at a frequency of 703.75 MHz. With a highly flexible electron beam return loop lattice, the R&D ERL will serve as a test bed for the technologies and concepts necessary for future high-current ERL-based projects. Emphasizing the R&D nature of the program further, the ERL is locally referred to as the “experimental cooling experiment” (ECX) cavity.

The ECX five-cell cavity has very long, large diameter beam tubes which connect to the room-temperature higher-order-mode (HOM) dampers that are installed outside of the cryostat. These HOM dampers use water-cooled ferrite absorbers. Results of the studies of HOM damping at room temperature with these ferrite absorbers have been published previously [6]. Since then, several tests have been performed to find the achievable peak field and the cavity

losses at 2 K, with the study of HOMs only a collateral goal. Thus, the lack of an attached refrigerator limited the time allotted for the collection of HOM data for this paper, and therefore efforts were focused on the two lowest dipole passbands.

The contemplated eRHIC electron accelerator would use SRF linacs based on five-cell SC cavities with highly damped HOMs, similar to that used for the R&D ERL. The cost of the SRF linacs and their real-estate gradients are the key consideration in this project. The eRHIC-type SRF cryomodules should also be compact and modular. Having gained experience with ferrite dampers at the ECX, various alternative approaches including capacitive HOM dampers are being explored.

This paper, an expanded version of a conference paper [7], is organized as follows. Section II summarizes the results from cold ERL measurements, and gives a table of HOM dipole shunt impedances for use in beam-breakup studies. In Sec. III, issues related to a modular design of future SRF linacs are addressed. The measurements of HOM damping achieved with capacitive probes placed at one or between two five-cell copper cavities are presented in Sec. IV. Section V reports on the same measurements performed with a ferrite absorber. Finally, Sec. VI is dedicated to describing a novel damper configuration with a ferrite absorber placed over a ceramic vacuum chamber, constructed for the SRF electron gun. The paper concludes with a short summary of the pertinent properties of the various absorbers studied.

II. THE R&D ENERGY RECOVERY LINAC

The Brookhaven R&D ERL (ECX) five-cell cavity is shown in Fig. 1 in its stage as vacuum string assembly with

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FIG. 1. View of ECX five-cell cavity vacuum string assembly with ferrite dampers, but without its cryostat. HOM signals are obtained from a pickup (PU) probe, beam position monitor (BPM) buttons, and the fundamental power coupler (FPC).

ferrite dampers, but without a cryostat. As seen in the figure, the two sets of beam position monitors (BPM), located at each side of the cavity vacuum string, are intended for centering the beam during operation. At the same time, the capacitive BPM buttons are available to collect the HOM cavity data, and in fact provided the strongest signals in the fully assembled and installed cavity. Each of the BPMs has three pickup probes spread evenly around the circumference, 120-degrees apart

(referred to in the text as 2-, 6-, and 10-o'clock BPM probes). The pickup (PU) probe serves primarily as a monitor of the fundamental field strength but being located near the cavity end cell and in spite of its high external Q ($\sim 3 \times 10^{11}$) provides HOM signals. In addition, depending on the operational mode, there was limited access to the fundamental power coupler (FPC).

The HOM frequencies and Q values of the cavity string with its ferrite dampers were obtained with the aid of a network analyzer, Agilent E5701C, from forward scattering coefficient (S_{21}) measurements between the bottom “6 o'clock” BPM probes located at opposite sides of the cavity. To study the beam-tube resonances, the two probes at “2 and 10 o'clock” from the same BPM were employed.

Mode identification and the determination of SC dipole shunt impedances was performed off-line by model runs in the CST MICROWAVE STUDIO (MWS) program [8] and by correlation with room-temperature copper cavity results. The HOM structure and parameters are established by the basic shape of the cavity, but are modified by the large aperture, 24 cm diameter, and the asymmetric lengths, 55 and 52.5 cm, of the beam-tube sections connecting the ferrite dampers to the cavity, as detailed in Fig. 2.

FIG. 2. The cross section of the ECX five-cell cavity vacuum string assembly (dimensions are in mm).

A. Measurement data

Normal conducting ECX cavity.—Figure 3 shows the HOM spectrum in the first two dipole passbands with the cavity at room temperature. The cavity resonances are identified as peaks in the S_{21} “through” measurement (BPM 6-6), and as dips in the “local” BPM measurement (BPM 2-10). The five proper cavity resonances, excited simultaneously in all five cells, are seen in the through signal, although the $4\pi/5$ and the π modes are smeared out and overlap due to strongly damped low Q values. The local measurement represents the transmission signal for the capacitive coupling between the BPM probes, which is nominally flat but is reduced at a resonance by power pulled into the cavity or beam tube. The local S_{21} signal in Fig. 3 shows the five resonances of the first dipole passband, plus an unexpected dipole resonance in the beam tubes at ~ 775 MHz. Mode identification, which is establishing correlation between data and MWS simulation, is possible for the two lowest passbands but increases in difficulty with frequency, and already the second passband does not allow obvious assignments.

As an illustration of the mode identification task, the field patterns simulated by the MWS for two dipole modes are shown in Fig. 4. One indexed as 775 MHz represents an additional mode below the cutoff frequency of the beam tube. It is seen as a beam-tube mode reaching into the larger radius end cell but not into the rest of the cavity. Another at 957 MHz is a “quasi” trapped mode constrained in the cavity with minimal fields at the absorber.

An expanded frequency plot of the ~ 775 MHz beam-tube resonances is shown in Fig. 5. The S_{21} structure of the downstream pipe, housing the fundamental power coupler (FPC), has notches characteristic of standing waves caused

FIG. 3. HOM spectra of the ECX cavity at room temperature. The red curve shows the transmission through the cavity (BPM 6-6), while the black curve shows transmission between two probes in the upstream tube (BPM 2-10).

FIG. 4. Plots of the longitudinal electric field component at 1 cm off axis for a dipole beam tube mode (red), and for a quasitrapped mode (blue). The fields are plotted against the location of the cell centers.

FIG. 5. Resonances in the upstream (blue) and downstream (red) beam tube. The latter houses the FPC. Its additional resonant structure is caused by the FPC’s waveguide connection to the rf source.

by reflections in the long waveguide connecting the rf power source to the FPC.

Superconducting ECX cavity.—Figure 6 compares the S_{21} spectra of the two lowest passbands of the five-cell cavity in the normal-conducting (NC) and superconducting (SC) states. Most NC measurements were performed after the SC tests during warm-up (before reaching room temperature). The modest increase in Q values between these states clearly indicates that the ferrite absorbers provide effective HOM damping for the majority of the modes. Only the quasitrapped 957 MHz mode is not sufficiently coupled to the ferrite absorbers (see Fig. 4) and has a relatively high Q ($\sim 50\,000$). Figure 7 shows its spectrum at room temperature, at 4 K, and at 2 K taken with ~ 6 points per kHz to make high Q values visible. Because of the smaller losses, the quasitrapped mode at the left shows

FIG. 6. Spectra of HOMs of the ERL five-cell cavity in the normal conducting (NC) and in the superconducting state (at 4 K).

a significantly stronger transmitted signal at 2 K in comparison to the neighboring damped resonance. Furthermore, note the clean frequency splitting due to the two polarizations of the dipole resonance.

FIG. 7. Comparison of the resonance curves of the quasi-trapped mode (left) with the neighboring damped mode (right). The direct Q measurements at left are 9 500, 44 200, and 47 800 for NC, 4, and 2 K. Also seen is the frequency shift in the left resonance due to the cooldown.

B. Data analysis and simulation results

Measurements of the cavity provide the HOM frequencies and Q values, but fall short of providing the impedances, i.e., the R/Q . The R/Q values are important for estimating the transverse beam breakup (TBBU) instability threshold of the beam, given as a limit on the shunt impedance $R_{SH} = (R/Q) \times Q_{HOM}$. Thus, the shunt impedances must be obtained through MICROWAVE STUDIO (MWS) simulations [8]. A picture of the cavity model used in these simulations is shown in Fig. 8. The MWS simulation results for the dipole R/Q of a cavity are obtained from the longitudinal electric field integral done off axis at $a = 1$ cm. In contrast to the convention for circular accelerators, the transverse impedances are given for TBBU studies in units of Ω per cavity and are interpreted as [9]

$$(R/Q) = (R/Q)_{1\text{ cm}} / (ka)^2 \quad (1)$$

with wave number $k = \omega/c$.

The HOM shunt impedance $R_{SH} = (R/Q) \times Q_{HOM}$ is then obtained using the simulated R/Q multiplied either by the measured Q_{SC} (when available) or by a simulated Q_{HOM} . Simulated Q values are quoted as Q_{FRT} when the model is run with the ferrite properties or as Q_{WGT} when the model is run with a waveguide termination.

In general, simulations of the cavity in the presence of ferrite material are time consuming. To circumvent program problems, the HOM frequencies were simulated in a first pass for a copper cavity without ferrite. In order to lower the run time, the dipole polarization was defined by enforcing $E_x = 0$ in the vertical plane through the cavity axis. The simulation runs for critical modes were performed in the Jacobi-Davidson method eigenvalue solver with the hexahedral mesh type and at least eight lines per wavelength. This mesh setting produced the lowest acceptable mesh size, $\sim 200\,000$ mesh points, of which about 2/3 were located in the ferrite absorbers. Runs with $\sim 100\,000$ mesh points only gave a 10^{-3} accuracy in the HOM frequencies, and $\sim 10\%$ in the R/Q accuracy. Subsequently, the study focused on individual resonances with ferrite absorbers, using the material properties of $\epsilon = 13$ and $\mu \approx 29/(1 + j2.6f_{\text{GHz}})$ leading to the setting of $\mu = 4(1 - j2.5)$ at 1 GHz for the MWS simulations [6].

Measurements and simulations for dipole modes in the two lowest passbands that dominate the beam breakup studies are summarized in Table I. A few explanatory comments are given here.

FIG. 8. Model of the ECX five-cell cavity used for MWS simulation.

TABLE I. Dipole modes in the R&D ERL cavity. Q_{WGT} and Q_{FRT} are simulated with a waveguide and ferrite dampers.

Data				Simulations					
f_{2-12} [MHz]	f_{6-6} [MHz]	Q_{NC}	Q_{SC}	f [MHz]	$R/Q_{1\text{ cm}} \times 10^3$ [Ω]	R/Q [Ω]	Q_{WGT} [Ω]	Q_{FRT} [Ω]	R_{SH} [Ω]
770				752	3.2	0.13	174	382	49
780				755	3.6	0.14	18	322	46
808	808.4	900	874	806	1.4	0.05	611	586	28
826	825.9	370	386	825	20.8	0.70	174	335	233
850	849.6	130	141	852	432.1	13.6	89	605	8225
878				875	1777.8	52.9	18	433	22 921
894				890	1593.3	45.6	15	176	8020
959	960.2	9500	47 800	958	2.0	0.1	2820	44 391	2216
966	966.4	3350	4720	964	103.9	2.6	927	6683	17
978	978.3	630	730	976	317.6	7.6	379	2288	17 392
998	995.6	205	326	993	98.9	2.3	9	1735	3969
				1026	4.0	0.1	9	67	6

The resonance frequencies, labeled f_{data} , are measured with the network analyzer between the bottom BPMs as shown in Fig. 3 (f_{6-6}), or locally in the upstream BPM (f_{2-12}). The difference between the simulated and measured frequencies is significantly larger than expected and can reach the MHz range. This difference is attributed in part to the mechanical contraction from the temperature change during cooldown but primarily to the lack of a detailed 3D model for the FPC and the BPM probe structures. Some MWS predicted resonances were not found in the measurements. Probable explanations for these discrepancies are (a) weak coupling of the probes to the fields of strongly asymmetric modes, and (b) lowering of Q due to an apparent broadening of the rotated split modes.

The R/Q values from simulations with and without ferrite can differ by low-digit factors, nevertheless the lossless values are usable for transverse beam breakup estimates. Furthermore, the accuracy of the simulated Q_{HOM} values and thus the R_{SH} is also limited. In the Q_{FRT} column, the use of approximate ferrite properties and the replacement of the ferrite tiles by a cylindrical ring lead to several cases, in which the MWS model underestimates the strengths of the ferrite damping and overestimates the Q values in relation to actual measurements. The Q_{WGT} column is obtained with a waveguide termination to represent the Q external of a perfect damper but is too optimistic in the case of the ECX cavity. The use of a perfect damper serves primarily as a guide for cavity design comparisons.

Table I covers the two lowest dipole passbands in the 0.75–1 GHz frequency range. The lowest frequency (0.75–0.9 GHz) passband is essentially comprised of hybrid TE_{11} modes that couple strongly to the propagating TE_{11} mode in the beam tube connecting to the ferrite absorber and, consequently, has low Q values. The number of seven modes found in the simulation with the same polarization exceeds the expected five cavity resonances. The additional modes are either beam-tube modes, end-cell

modes, or longitudinally split asymmetric cavity modes. The two beam-tube modes at ~ 770 MHz are confined to either cavity end. The second passband (0.95–1.0 GHz) is comprised of hybrid TM_{11} modes with weaker coupling to the TE_{11} beam-tube mode and the ferrite absorber, and correspondingly higher Q values. The quasitrapped mode in the beginning of the second passband at ~ 960 MHz is a typical example of a HOM with weak coupling to the absorber.

Estimated TBBU limit

The five-cell ERL cavity, together with a half-cell photo-injector SRF electron gun, is intended as a demonstration for the envisioned electron-hadron collider, eRHIC. This paper presents preliminary HOM results obtained from the limited number of cooldowns of the cavity (presently the only ERL facility component available). A fraction of the HOM resonances was analyzed by aid of the MWS program. Figure 9 summarizes the measured and mode-identified data (red delta) together with simulated R/Q values in the frequency range from 750 to 3100 MHz. Further cooldowns will extend the measured data list.

FIG. 9. Simulated R/Q values, transverse shunt impedance values, and the estimated worst-case BBU limit.

Also shown in Fig. 9 is the estimated impedance limit set by the transverse beam breakup (TBBU) for the completed ERL facility. The limit is discussed in terms of the worst-case scenario that restricts the impedance value to $R_{SH} \ll 2c^2/(e\omega T_{12}I)$, where I is the beam current and T_{12} the transfer matrix element [10], taken here as $T_{12} \approx 5$ m, which is as large as achievable without significantly increasing the beam size in the cavity [11]. The transverse impedance, quoted in Ohm per cavity, $R_{SH} = (R/Q)_{MWS}Q_L$ is obtained with the loaded Q_L from measured data at 2 K, if available, or from simulations with ferrite damping. More detailed BBU studies with the magnet optics included show that mainly a few proper cavity dipole modes are the culprits that impose the tolerances on the Q_{HOM} values.

III. CAVITY STRING MODEL

The envisioned eRHIC facility would combine the existing hadron ring with an energy recovery linac to produce the electron-ion or e - p collisions. The eRHIC ERL is planned for a one-pass electron current of 50 mA and to reach full energy at 20 GeV after four passes. The present concept views the electron linac as a chain of cryomodule sections, with each cryomodule (Fig. 10) employing six five-cell cavities. Beam breakup (BBU) induced by HOMs is a critical issue for high-current ERLs, and is particularly challenging for multipass ERLs. The R&D towards this machine was thus concentrated on the development of a new efficient, but highly damped cavity with appropriate HOM dampers. Having gained experience with ferrite dampers in the ECX cavity, the scope was extended and the primary focus in the present study is to explore alternative, primarily capacitive HOM dampers.

A. ERL cavity design improvements

The SC cavities will be of the type being used in the present five-cell ECX (BNL1) cavity. New ERL cavities were designed with the goal of minimum HOMs [12,13]. The optimization process for one new cavity, BNL3,

resulted in increasing the R/Q of the fundamental mode from 400 to 500 Ω per cavity while remaining under an acceptable magnetic field level of $B_{peak}/E_{acc} \leq 4.26$ mT/(MV/m). Changes in the center and end-cell geometry were used to reduce the R/Q of critical harmonics and to prevent trapped modes. The new cavity retains the present concept of providing a large aperture, 22 cm, beam tube that allows lossless propagation of all HOMs to the damper while attenuating the fundamental mode. Sufficient length of the beam tube is required to attenuate the fundamental to an acceptable power load at the damper. The damper design must provide good coupling of HOMs in the beam pipe and act as a fundamental filter.

The MWS models for the BNL1 and BNL3 shown in Fig. 11 highlight the difference in their geometry, consisting mainly in a change of the wall angle bringing BNL3 closer to a “low-loss” cavity. The HOM impedance projections for these cavities are produced with MWS simulations for the two models, and the progress in cavity design is seen in Table II, where frequencies and simulated external Q values of the two lowest dipole passbands in the old and new cavity are compared. The achievable damping of the HOMs in the two cavities is based on simulations with attached “perfect” dampers that are generated by adding waveguide ports to evaluate the external Q_X . The simulated values for Q_X are significantly lower, indicating better coupling of the HOMs to the dampers.

The HOM frequencies are presented as a Brillouin diagram in Fig. 12. Since it is known that dipole passbands can exist as forward or backward waves [14], the sorting is done here by finding the modes with zero phase shift per cell, the “ $0\pi/5$ ” modes. The on-axis transverse electric field for the hybrid TE_{11} passband in the BNL1 and BNL3 models is shown in Fig. 13, providing an unambiguous (no sign reversal) plot for a $0\pi/5$ mode at the lowest frequency of a forward wave.

The BNL1 design was based on the concept that a large beam-tube aperture, here 24 cm, allows for the exit of HOMs from the cavity to the damper, a fact that was confirmed by various measurements. This approach is

FIG. 10. An energy recovery linac cryomodule with six cavities.

FIG. 11. The models for the BNL1 (top) and BNL3 (bottom) cavities.

TABLE II. HOM frequencies and Q 's in ERL cavities. External Q_x are simulated with waveguide ports.

f [MHz]	BNL1			f [MHz]	BNL3		
	Q_x	R/Q [Ω]	$(R/Q)Q_x$ [Ω]		Q_x	R/Q [Ω]	$(R/Q)Q_x$ [Ω]
792.3	4	1.9	8	815.4	245	0.7	176
792.8	4	0.2	1	818.4	110	1.2	131
810.2	890	1.1	955	835.2	73	1.2	87
830.0	212	0.3	69	854.2	80	0.6	52
856.0	99	25.8	2561	873.3	57	17.0	960
880.7	95	67.1	6353	896.7	7	39.3	258
916.1	32	46.6	1510	927.9	51	35.4	1789
916.5	29	2.9	83	957.1	81	2.1	173
958.7	22 900	0.0	790	988.9	173	28.7	4972
964.7	2670	2.5	6659	1008.6	308	35.5	10 946
976.2	683	8.0	5484	1019.1	545	8.3	4548
992.6	593	2.3	1341	1023.1	747	1.3	964

retained for the BNL3 cavity shown in Fig. 14 with its 22 cm diameter beam tubes and 7.8 cm end-cell exit radius. However, the large diameter of the beam tube allows the generation of beam-tube resonances, with an example shown in Fig. 15. Beam-tube modes are measured locally with the BPM probes at one cavity end and are damped, but depending on the field configuration can also reach into the end cell and maintain a high Q .

A further design concern stems from the possible existence of trapped modes that are uncoupled to the damper. Thus, BNL1 at 958 MHz is a prototypical example of a quasitrapped “proper” cavity mode whose fields are concentrated in the center cell with minimal coupling to any damper in the adjacent beam tube. The resonance of this mode is shifted in BNL3 from 958 to 1019 MHz but the field shape has remained essentially unchanged as demonstrated with the longitudinal electric field at 1 cm offset in

Fig. 16. Although only weak tails of these fields extend outside the cavity towards the dampers and allow relatively high Q values, the low R/Q assures tolerable transverse shunt impedance.

FIG. 12. Brillouin diagram for the BNL1 and BNL3 cavity models.

FIG. 13. On-axis transverse electric field of the $0\pi/5$ modes in BNL1 and BNL3. The fields are plotted against the location of the cell centers.

FIG. 14. MWS models for the BNL3 cavity with 22 cm diameter beam tubes and end tapers as presently being fabricated.

FIG. 15. Simulated accelerating field (E_x @ 703 MHz) and transverse electric field (E_z @ 1023 MHz) of a beam tube HOM resonance in the BNL3 cavity. Also shown are the cell centers (red) and the location of the cavity with the beam tubes (blue).

FIG. 16. Quasitrapped modes in the BNL1 and BNL3 cavities. The fields are plotted against the location of the cell centers and the damper.

B. Coupled cavities

Technical and financial considerations for the eRHIC point to a design with highly compact, modular cryomodules and accompanying structures. The present concept views the electron linac as a chain of the cryomodule sections in Fig. 10. Interconnecting cavities present several problems different from or not encountered in a single cavity that deserve to be researched anew. The design of the beam tube between the cavities will have a pivotal impact on the performance of the facility. The limited

available real estate practically imposes placing the HOM dampers into the cold section between two cavities. Replacing ferrite with capacitive probes is one option for longitudinal space savings in a chain and represented the stimulus for the studies in this paper. The availability of two five-cell copper cavities provides an opportunity for exploratory damper measurements applicable to the chain, which are sufficiently replicated by the two-cavity arrangement in Fig. 17. Since in the ECX cavity the measured and simulated loaded Q values for the proper cavity HOMs agreed sufficiently, the remaining study of coupled cavities can be done with the Cu models without the ferrite.

Connecting cavities while maintaining the full beam-tube aperture results in a frequency shift and splitting of the HOMs in neighboring cavities. This is clearly seen in Fig. 18 with the HOM spectrum of two undamped Cu cavities, joined together directly. Depending on the inserted beam-tube length between cavities, coupling even at the fundamental mode frequency must be considered. Inserting a 12.7 cm long spacer ring between the Cu cavities is sufficient to decouple the fundamental. The taper in BNL3, too, would minimize or remove the HOM coupling.

A major objective in designing HOM dampers is minimizing the associated fundamental mode losses. In the

FIG. 17. The HOM damper ring with capacitive probes between two copper cavities.

FIG. 18. Frequency splitting of HOMs in the combined ERL Cu cavities.

ECX cavity, this was achieved by placing the ferrite damper sufficiently far away from the cavity proper. Such a design is not appropriate for a space-constrained string. The solution with capacitive HOM dampers places the probes in proximity to the cavity and will necessitate a selective filter, permitting HOM power transported to room temperature while avoiding loading of the fundamental.

Alternatively, the filter problem is alleviated by applying the concept of canceling the evanescent waves in the inter-cavity space [15]. Providing individual excitation of cavities and placing the center of the end cells apart by $(n + \frac{1}{2})\lambda \approx 64$ cm for $n = 3$ produces a fundamental field minimum between the beam tubes. Thus, placing cold dampers at the center of the inter-cavity space results in minimum fundamental mode coupling, but will require symmetric beam-tube extensions. However, in order to take full advantage of this solution, some additional constraints must be respected. Simulation with the ECX cavities at the optimum spacing showed strong coupling at the fundamental with frequency reduction of about 2 MHz, a frequency splitting of 2 kHz between the even and odd inter-cavity fields, and a R/Q reduction of $\sim 3\%$. Inserting a short reduced aperture section with long tapers to the cavity end is expected to suppress any disturbing cavity coupling.

IV. CAPACITIVE HOM DAMPERS

The search for alternate HOM damping methods points to capacitive probes (antennas) and inductive loops. Because of their simpler construction, capacitive probes have been studied here as dampers in copper cavities. In contrast to ferrite dampers, the capacitive probes can be superconducting and would be placed in the cold section between two cavities while attached to a 13 cm long spacer ring as shown in Fig. 19. The damper ring is equipped with four capacitive “mushroom” probes, each with a 51 mm diameter disk on a 25 mm-long stem. Two versions have been tested, one has the four capacitive probes centered in the ring and placed 38 cm from the left, and 42 cm from the right cavity end. This spacing between end cells would require ~ 1.65 m per cavity module in the chain and exceeds the optimum for evanescent cancellation. The other damper ring version, shown in Fig. 20, has the probes axially staggered.

FIG. 19. Connecting tube with damper ring between Cu cavities.

FIG. 20. Damper ring with four mushroom capacitive probes each with a 51 mm diameter disk on a 25 mm-long stem. A 1 ft ruler is added for scale.

The effectiveness of one mushroom probe is expressed by its Q external and is found from the S_{21} transmission coefficient between the two fundamental power couplers, FPC1 and FPC2 in Fig. 17, thus yielding data for the left cavity. The Q external is obtained from the unloaded Q_0 and loaded Q_L as

$$Q_X = \frac{Q_0 Q_L}{Q_0 - Q_L}. \quad (2)$$

The measured frequencies and Q values for this setup are listed in Table III, where the simulated frequencies for one

TABLE III. Simulated and measured frequencies and measured Q values of the cavity with one ring. Q_X is from Q_0 and Q_L . $Q_X(\text{wo})$ is for probes with equal length but without disk. The external Q at the fundamental is $\sim 10^8$.

f_{MWS} [MHz]	f_{data} [MHz]	Q_0	Q_L	Q_X	$Q_X(\text{wo})$
808.8	806.3	11 370	9940	79 033	311 822
	814.3	7090	5310	21 151	125 194
826.2	825.1	17 050	4190	5555	42 889
	828.6	9450	2490	3381	24 249
849.1	847.1	13 440	3610	4936	44 270
	852.8	10 980	1680	1983	17 521
870.1	867.9	10 520	2770	3760	35 593
883.3	877.2	13 570	2603	3221	38 448
890.1	884.3	7990	3290	5593	50 046
959.4	958.2	35 390	29 460	175 816	4 283 000
	958.7	34 900	2880	138 606	5 501 500
965.7	965.6	23 950	17 760	65 027	26 151
977.6	976.7	19 370	3440	4183	124 384
	978.0	23 400	13 000	29 250	165 414
994.4	994.5	1340	1100	1199	8335
	996.8	15 090	4840	7125	71 821

single Cu cavity are added as guidance. The Q external measured here can be expected to equal the loaded Q in a SC cavity for the determination of the shunt impedance. The column indicated by $Q_X(\text{wo})$ is obtained with probes of equal stem length but without disks, and its higher values point to the 51 mm diameter, 25 mm long capacitive probes as being the appropriate dampers. Placing damper rings at both ends of the cavities should halve the Q values.

The fields of the HOMs in the beam tube are stationary, even though they are above cutoff, and the coupling field component is prone to have nodes. The axial location of the probes thus determines the coupling strength and a damper of finite axial length has a better chance of connecting to the HOM mode. As a finite-length approximation, the probes in the ring were displaced pairwise from the center by ± 35 mm as seen in Fig. 20. The measurement with staggered placements of the four probes was performed and the results, listed in Table IV, indicate improved damping. The frequency spectrum for one staggered capacitive damper ring between the two cavities in Fig. 19 is shown in Fig. 21.

Since dipole HOMs are polarized, a diagonally arranged probe pair can miss one polarization. In contrast, dampers with three probes per ring in one plane at 2, 6, and 10 o'clock, or at 4, 8, and 12 o'clock assure some coupling to the modes. Combining three-pronged probes as a six-pole staggered “porcupine” would be optimum.

A pivotal consideration in designing HOM dampers is to minimize the collateral fundamental mode losses. The HOM damped Q_X in Table III provided by each probe is combined with a fundamental external cavity $Q \sim 1 \times 10^8$, that would be unacceptable in the presence of six to eight probes in one cavity. The Q external at the fundamental mode attributable to one probe in the ring and

TABLE IV. Measured frequencies and Q values with staggered dampers.

f_{data} [MHz]	Q_0	Q_L	Q_X
808.0	5810	3260	7428
808.6	4260	2520	6170
819.3	5660	4460	21 036
825.0	17 920	100	101
833.0	9740	4970	10 148
846.2	12 440	1540	1758
854.6	11 310	3280	4620
865.8	3420	10	10
877.0	12 180	1400	1582
883.2	6300	2040	3017
958.7	33 040	22 790	73 462
965.5	28 650	4830	2809
976.9	13 050	100	101
877.8	15 670	1850	2098
995.0	8660	3880	7029
996.4	8770	2240	3008

FIG. 21. Frequency spectrum of a capacitive damper ring with staggered dampers between Cu cavities.

its dependence on geometry and location was measured and is shown in Fig. 22. The length of the damper ring and its location with respect to the cavities is a critical design parameter, and must be selected for strong damping,

FIG. 22. Q external of fundamental versus damper position and probe size (disk diameter $\times$ stem length $\times$ stem diameter in mm), probe position is defined in Fig. 19.

FIG. 23. Sketch of a capacitive HOM damper with a high-pass filter attached (dimensions in mm).

together with the shortest overall module length and minimum coupling to the fundamental. The capacitive ring already adds ~ 13 cm to the cavity's length. An order-of-magnitude reduction of the fundamental load would require adding about 8 cm to the length of the beam tube.

The standard alternative in a real-estate limited situation is to provide a high-pass or notch filter at the HOM damper that restricts fundamental loading. The high-pass filter must block the fundamental at ~ 703 MHz while allowing passage at 800 MHz, implying a steep transition of better than 60 dB. A first design for the five-cell cavity followed the antenna HOM coupler for HERA [16] and had adequate suppression of the fundamental [17]. Another configuration, mechanically simpler, is shown in Fig. 23. Preliminary tests were performed and will serve as a guide for increasing the transition between the fundamental frequency and the HOM high pass.

Since the damper ring with its probes is located close to the FPC in a cavity chain without “waist,” cross coupling at the fundamental between FPC and the damper probe must be considered in addition to HOM damping. Fundamental cross coupling between the FPC at the right cavity in Fig. 19 to a single damper at the ring center was found to be $S_{21} \sim 3 \times 10^{-3}$, complicating the thermal design of the fundamental filter.

V. FERRITE DAMPERS

Ferrite dampers are used successfully in the BNL ERL and must serve as a reference for any alternative solution. A photograph of the prototype ferrite absorber is shown in Fig. 24. The ferrite parameters are found in [6]. This absorber was placed between the five-cell copper cavities, as shown in Fig. 25, to provide a configuration that can be compared directly with a capacitive ring damper in Fig. 19. The setup for the S_{21} measurement between the FPC's at the cavities was similar to that in Fig. 17 for the capacitive

FIG. 24. Prototype HOM ferrite damper.

FIG. 25. Ferrite HOM damper installed between two five-cell Cu cavities.

damper ring and provided the excitation of the left cavity. In both cases, the free ends of the five-cell cavities were shorted by Cu plates to eliminate any radiation or coupling with the outside environment.

Table V lists the measured data for the ferrite-damped HOMs in the two lowest HOM passbands. The $Q_{2\text{cvtv}}$ column was taken for the ferrite damper ring between the cavities, and is next to the corresponding results, $Q_{1\text{cvtv}}$, for a single cavity with one ferrite damper, and then also for the ECX cavity, Q_{ECX} , with two dampers. The single cavity ECX configuration with one damper at each cavity end provides the strongest HOM damping.

The comparison of the damped Q values $Q_{2\text{cvtv}}$ and $Q_{1\text{cvtv}}$ reveals a qualitative difference in the first (hybrid TE_{11}) and the second (hybrid TM_{11}) passband and points to a strong dependence on the local field configuration. In this vein, it is also noted that one damper for one cavity does not provide the expected uniform damping at all frequencies. It is clear that the results are ambivalent but one can surmise that one ferrite damper between two cavities in the string would provide sufficient damping. In addition, it is

TABLE V. Parameters of ferrite-damped HOMs for the two-cavity string.

f [MHz]	$Q_{2\text{cvtv}}$	$Q_{1\text{cvtv}}$	Q_{ECX}
808.4	4690	1780	900
809.0	4380		
825.3	1480	415	370
849.1	910	120	130
858.2	130		
873.1	580	162	
879.3	410	332	
892.0	630	290	
897.9	2110		
958.1	13 210	22 300	9500
958.6	13 390		
964.7	1950	6670	3350
974.0	580	2000	630
985.9	460	1064	
1001.3	790	1512	205

noted in Fig. 26 that the ferrite decouples the two cavities enough to suppress the mode splitting without the need for a waist.

The contrarian indication to the application of ferrite stems from the cooling requirements at liquid helium temperatures. The beam current induced heating consists

FIG. 26. Frequency spectrum of ferrite damper between Cu cavities.

FIG. 27. Surface impedance of the ferrite damper, treated as a cylinder with 6 cm inner diameter radius and unbound outer diameter (dashed), or with 3 mm wall thickness (solid). Ferrite parameters are $\epsilon = 13$ and $\mu = 29/(1 + j2, 5f_{\text{GHz}})$.

of the unavoidable HOM losses and the location-dependent fundamental power loss. The power deposited into the ferrite is obtain as

$$P = k_{\parallel} I q_B, \quad (3)$$

where I is the beam current, q_B the bunch charge, and $k_{\parallel}$ the longitudinal loss factor. The losses are bunch length dependent and are taken as ~ 2 mm rms for the present estimate. The HOM loss factor for BNL1, $k_{\parallel} \approx 3.5$ V/pC [5], was obtained via the azimuthal beam cavity interaction (ABCI) program and the ferrite loss factor $k_{\parallel} \approx 1$ V/pC by integrating the ferrite surface impedance shown in Fig. 27. The four-pass eRHIC option with a one-pass current of $I = 50$ mA and 3.5 nC bunches would generate about 5 kW from HOMs plus 1.5 kW from the ferrite impedance. It is evident that disposition of this amount of power into the 2 K cryogenic system must be prevented by an appropriate damper configuration with the ferrite placed at room or liquid nitrogen temperatures.

VI. FERRITE DAMPER WITH CERAMIC BREAK

The ferrite dampers at the ECX cavity are at room temperature and the HOM deposited power is removed by water cooling while fundamental power is minimized by sufficiently long beam tubes. Attaining high real-estate gradients in a cavity chain precludes increasing the length of the vacuum tube between cavities sufficiently to allow the evanescent fundamental mode to decay to a tolerable level at the damper. An innovative method to use ferrite at nonsuperconducting temperatures without loss of space was found by placing a ceramic break in the cold beam tube under the ferrite absorber.

This concept of a ferrite damper with ceramic break is sketched in Fig. 28. The ceramic tube is a low-loss alumina (Al_2O_3), and the ferrite tiles are brazed to a metal plate as

FIG. 28. Ferrite HOM damper with 10 cm inner diameter ceramic break. The plates with ferrite tiles are held in place by the clamshell holder (dimensions are in cm).

done for the ECX absorber in Fig. 24. The clamshell holder represents the thermal transition and its design, size, and material is crucial to minimizing the total heat load. The main problem in this configuration, next to thermal isolation of the ferrite from the beam tube, is the need for coating of the ceramic tube to prevent static electron charge accumulation. The ceramic must be sputter coated with 321 stainless steel, about ~ 1 nm thick and end to end resistance > 10 k Ω . The ceramic can serve as an effective electrical and thermal transition, and brittle ferrite material is moved outside the particulate-free SRF-class vacuum. The multilayer structure of such an absorber was analyzed, and it was proved that the damping properties of such a system remain acceptable [18].

If used in a cavity chain, the ferrite would be located in the cryostat insulating vacuum, and the cooling of the ferrite is simplified by placing it outside the 2 K cryogenic line, thus allowing higher temperatures, even liquid nitrogen. When combined with the cavities properly spaced to reduce the fundamental coupling, the ferrite with ceramic break is exposed to minimum heating and has the further advantage of reducing the coupling of neighboring cavities.

A ceramic break will be provided at the SC photoinjector [4] for the R&D ERL facility. Although at room temperature, it will provide for the attachment of ferrite absorber plates as a demonstration of the basic concept. A prototype of such a ceramic break–ferrite absorber has been fabricated and was attached to a spare large-crystal Nb gun cavity. Figure 29 shows the prototype damper at its top with some ferrite tiles removed to expose the ceramic

FIG. 29. The ceramic-ferrite damper with some ferrite tiles removed (top) and the SRF gun with the ceramic-ferrite damper assembled (bottom).

break free and then at the bottom attached to the ERL gun fully assembled. The ferrite tiles, located outside the tube in the atmosphere, will be cooled by forced air flow. The design of a “clamshell” structure that holds the ferrite tiles in place allows for their replacement and the addition of other damping materials that may be installed and tested. Preliminary tests confirmed damping of gun resonances by the ferrite-ceramic break [19]. Figure 30 compares Q values in the absence of the damper (black) with the ferrite added alone and also with the ferrite-ceramic combination (blue). Only resonances that can propagate in the 10 cm diameter beam tube reach the damper successfully. More definite measurements are expected in the next year with beam from the gun.

VII. SUMMARY

The prospects for future RHIC upgrades, be it an electron-ion collider or coherent electron cooling of

FIG. 30. Damping of dipole gun resonances (black) by ferrite alone (red) and by the ceramic/ferrite combination (blue).

protons, depend on achieving high-current and high-charge electron linacs. The design of effective HOM dampers for these projects is one of several critical ongoing R&D efforts at this laboratory. Multipronged design activities include the development of ferrite-loaded waveguide dampers, capacitive probes/antennas, and ceramic/ferrite-loaded waveguide dampers. The technical solution for HOM dampers will largely be dictated by the choice for the disposal of the beam induced fundamental and HOM power. The use of room-temperature ferrite absorbers has been demonstrated at the Brookhaven ERL facility but becomes prohibitive at SC temperatures. Operation of ferrite at liquid nitrogen temperatures reduces the 2 K heat load but needs thermal transitions and adds to the cavity chain length. Adopting capacitive dampers together with fundamental filters avoids the fundamental power load and represents an attractive solution, but requires a multiple of damper probes to equal one ferrite ring. Reducing the fundamental power at the damper via cancellation of the evanescent beam-tube modes by proper spacing of the cavities is being considered both for capacitive and ceramic/ferrite dampers. In summary, concepts and results for HOM dampers relating to the envisioned future projects at this laboratory are collected in this paper to serve as a source for the remaining necessary R&D and the mechanical and cryogenic engineering work.

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